CONTINUED RESEARCH ON SELECTED PARAMETERS TO MINIMIZE COMMUNITY ANNOYANCE FROM AIRPORT NOISE

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ABSTRACT

A mathematical model of the annoyance created at an airport by aircraft operations is developed. The model incorporates population distribution considerations around an airport and the annoyance caused by aircraft noise. The objective function of this model corresponds to seeking to minimize total population annoyance created by all aircraft operations in a 24-hour period. Several factors are included in this model as constraint relationships. Aircraft operations by type and time period are upper bounded. Demand for flight services is incorporated by including lower bounds on the number of operations by type of aircraft, runway used and time period. Also upper bounds on the number of operations for each runway are included. The mathematical model as formulated is recognized as corresponding to a nonlinear integer mathematical programming problem.

The solution technique selected makes use of a successive linear approximation optimization algorithm. An especially attractive feature of this solution algorithm is that it is capable of obtaining solutions to large problems. For example, it would be feasible to attempt the solution of problems involving several thousand variables and 500 plus linear constraints. This suggested solution algorithm was implemented on a computer and computational results obtained for example problems.

I. INTRODUCTION

With the advent in the late 1950's of the jet-engined commerical aircraft, airports began facing an increasing noise pollution problem. As aircraft size and range increased there was a corresponding increase in the number of commercial routes over which these carriers operated. More routes dictated more aircraft, so existing airports were required to handle an increased volume of air traffic each year. New airports were constructed to meet the ever increasing demand for air transport, and the older, less scientifically designed airports continued to handle higher and higher volumes of traffic.

Airports were designed to handle not only increased volumes of air traffic but also larger aircraft. What the airports, up to this point, have not been able to satisfactorily handle is the associated noise pollution. As the noise pollution has increased, so has the opposition to the noise. This opposition has become well organized and has addressed not only noise levels within airport boundaries, but noise pollution in the acreage surrounding airports as well. Noise, or more specifically the reduction of noise around airports has become a critical economic as well as emotional issue.

As with most of today's complex issues there is not an easy solution to the problem of aircraft noise. In fact, there is not even a consensus of opinion as to what constitutes the best solution. Individuals who are annoyed by the noise argue that the noise is interferring with their lives and affecting their property values; they implore the airports and airlines that fly into them to reduce the noise to an acceptable level immediately. The airlines argue that any short-term solution to the problem would be a

disaster to them economically and urge understanding until they can economically phase out their older, noisier jets and replace them with newer, quieter models. Airport managers say they are caught in the middle, sympathizing with the individuals who are annoyed by the noise, but powerless to individually effect a change on the airlines without strained relations and hard feelings.

The goal of this research is to determine the minimum noise impact assignment - scheduling of aircraft to the existing arrival and departure trajectories for any airport of concern. To support the modelling effort for the minimum noise formulation a considerable amount of background material is required. The next two sections contain this related material. The problem of interest is formulated via a mathematical model in section IV. The objective function of this model corresponds to seeking to minimize the total population annoyance metric as a function of aircraft operations in a 24-hour period. Factors such as aircraft operations, demand and time restrictions are included as constraint relationships. Section V presents a solution technique that makes use of gradient information and successive linear programming to obtain approximate noise minimal solutions. An attractive feature of this solution algorithm is that one can efficiently use it to produce solutions and sensitivity analyses for very large problems. Computational results are then presented for an application airport. These results are especially encouraging when compared with current operating scenarios. That is, they indicate a substantial reduction in airport community annoyance may be achieved by merely changing the assignments of servicing aircraft to the established arrival and departure trajectories.

II. BACKGROUND INFORMATION ON NOISE

II.1 Sound Measurement

The problem associated with the measuring of sound around airports is one of developing a rating scheme that will quantify the sound as acceptable or unacceptable to the human ear. The basic instrument used to measure sound is the sound level meter. If this sound level meter is used to measure sound regardless of frequency, called the Overall Sound Pressure Level, a measure called the C-Weighted Sound Level is derived. This meter permits one to obtain a reading that will be satisfactory in determining the sound acceptability and in rank-ordering various noises. Although the C-Weighted Sound Level is a measure of sound it does not correspond very well to the way individuals judge noises [12].

A measure of sound that more accurately corresponds to the way people judge noises is the A-Weighted Sound Level (L_A), or A-Level. This measure is expressed in decibels dB(A) and is the weighted sum of all of the components of the noise. This measure has been found to correlate very well to an individual's subjective judgment of the annoyance of many types of noise. Table 1 gives representative values of A-Weighted Sound [12].

II.2 Human Reaction to Noise

Much more difficult than measuring the sound is quantifying the human reaction to a measured noise level. Noise can have one of three effects on people: (1) Subjective (annoyance, nuisance, dissatisfaction, disturbance, etc.); (2) Behavioral (interference with an on-going activity); and (3) Physiological [12]. Table 2 depicts the noise levels that will most likely interfere with specific activities.

Even being able to measure noise satisfactorily and then knowing what

TABLE 1

Decibel Levels

Measure dB(A)	Perceived Loudness
0-10	Threshold of hearing
10-40	Barely audible
40-60	Quiet
60-80	Moderately loud
80-110	Very loud
110-130	Uncomfortably loud

Source: U.S. Department of Housing and Urban Development. "Noise Assessment Guidelines Technical Background." Report #TE/NA 172. Washington, D.C.

TABLE 2

Noise Interference

Activity	Average outdoor noise levels
Interference with Radio & T.V. listening with the windows open	45 to 50 dB(A)
Interference with Radio & T.V. listening with the windows closed	55 to 60 dB(A)
Sleep interference	40 to 45 dB(A)
Acceptable living environment	Less than 80 to 85 dB(A)

Source: U.S. Department of Housing and Urban Development. "Noise Assessment Guidelines Technical Background." Report #TE/NA 172. Washington, D.C.

levels of that noise will interfere with everyday functions is not totally sufficient. Studies have shown that approximately 10% of the population are so sensitive to noise that any noise not of their own making is objectionable to them. Conversely, it has been estimated that 25% of the population is virtually insensitive to noise and will not complain even in very severe noise environments [12].

Individual reaction to noise will depend on various items including previous noise exposures, psychological attitudes, socio-economic status and the nature of the activity that is intruded upon by the noise. Due to the disparity in these factors, any derived scale will be subject to inaccuracies and question. It is more important to look on a rating scale (or metric) as an attempt to describe, in physical terms, the nature and magnitude of the total noise as it affects groups of individuals. The scale is helpful in determining the level of noise stimulus that cannot be exceeded without rendering the environment unacceptable for living for most people [12]. Any scale will attempt to account for the context in which the noise stimulus is experienced and can well introduce various adjustments for characteristics of the noise and the situation on which the noise intruded.

II.3 Noise Measurement and Assessment

As has been discussed, a mere fluctuation in the needle of a Sound Level Meter cannot indicate the level of annoyance that particular sound will create in an individual. To quantify annoyance, noise exposure must be introduced. Noise exposure is defined as "the whole time-varying pattern of the sound level rather than some single level, such as the average value" [12]. Results of experiments show that a steady noise is more

acceptable to people than a noise of the same average level that fluctuates erratically. In most cases, the greater the fluctuation, the greater the annoyance. Several single-event noise measurement scales will be introduced and their relationship to the measurement and quantification of multiple-event scales, that can be used to assess the noise environment around an airport, will be specified.

II.4 <u>Perceived Noise Level (PNL)</u>

The PNL may be defined as "a quantity that is calculated from measured noise levels and adjusted by weighting more heavily those frequencies that are more annoying to the listener" [7].

$$PNL = 1.02\ L_A + 11.5 \qquad (1)$$

Where L_A represents the noise level in dB(A). The PNL is measured in PNdB. This measure is based on the individual judgments of "equal annoyance for bands of sound one-third octave wide during an aircraft flyover" [11].

II.5 <u>Effective Perceived Noise Level (EPNL)</u>

This scale, expressed in EPNdB is defined as a unit of perceived noise that "takes into account the actual sound energy received by a listener, the ears' response to that sound evergy, the added annoyance of any pure tones or 'screeches' in the noise, and the duration of the noise" [13]. The EPNL has been adopted by the Federal Aviation Administration (FAA) as a measure of the noise emission level of individual jet aircraft.

II.6 <u>Noise Exposure Level</u>

Another single event noise metric is the Noise Exposure Level (NEL). The NEL may be defined as the summation of the time varying sound level

over the time span the sound level is within 30 dB of the maximum. In equation form

$$NEL = 10 \log_{10} \int_{t_1}^{t_2} 10^{(L_A(t)/10)} dt \qquad (2)$$

where t_1 and t_2 correspond to sound levels of 30 dB less than the maximum sound. $L_A(t)$ corresponds to the A-level sound at time t.

II.7 Noise Exposure Forecasts

A method of measuring noise from multiple events around airports is called the Noise Exposure Forecast (NEF). The NEF may be defined as "the computed summation over a 24-hour period based on Effective Perceived Noise Level, the number of daytime (7 a.m. to 10 p.m.) aircraft noise events, and the number of nighttime (10 p.m. to 7 a.m.) aircraft noise events" [6]. This forecast "provides a measure of the total aircraft-generated noise received at locations near an airport during a typical 24-hour period" [13]. The NEF value may be represented mathematically as:

$$NEF_{ij} = (EPNL)_{ij} + 10 \log (N_{D_{ij}} + 17 N_{N_{ij}}) - 88 \qquad (3)$$

where the terms are defined as:

EPNL = effective perceived noise level for the particular aircraft at the given point on the ground, in decibels (A)

i = aircraft class

j = aircraft flight path

$N_{D_{ij}}$ = number of daytime events of the particular aircraft

$N_{N_{ij}}$ = number of nighttime events of the particular aircraft

Once these individual NEF values are computed, the total NEF value of a ground location is computed by the equation:

$$NEF = 10 \log \sum_i \sum_j \text{antilog } (NEF_{ij})/10 \tag{4}$$

Table 3 represents typical NEF values and the level of public complaint that such values will evoke. To scale the NEF values, one may think of the reduction of one NEF unit as the equivalent of the reduction of approximately 2% of the number of people who will be highly annoyed by the noise [13].

Once the NEF values of locations surrounding airports are computed, locations of equal NEF may be joined together to give NEF isopleths. It should be noted that the Federal Aviation Administration (FAA) has accepted it for land use planning around commercial jet transport airports [12]. Along with the FAA, the U.S. Department of Housing and Development (HUD) has published the guidelines in Table 4 as a site screening device for residential housing.

II.8 Day-Night Level

Day-night level (L_{dn}) was developed as a single-number measure of community noise exposure. It is defined as the average A-Weighted noise level integrated over a 24-hour period. Appropriate weightings are applied for the noise levels occurring in the daytime and nighttime periods [3]. It is stated in [15] that L_{dn} is "the primary measure for describing noise in an environmental impact statement". For discrete sampling of A-Weighted sound level for a 24-hour time period, L_{dn} may be formulated mathematically as,

$$L_{dn} = 10 \log \left[\frac{\sum_{i=1}^{n} w_i \text{ antilog } (L_{A,i}/10)}{n}\right] \tag{5}$$

TABLE 3

NEF Interpretation

NEF Value	Interpretation
Less than NEF 30	No complaint expected, noise may interfere with community activities.
NEF 30 to NEF 40	Individual may complain, group action possible.
More than NEF 40	Repeated vigorous complaints expected, group action probable.

Source: U.S. Department of Transportation. "Aviation Noise Abatement Policy." Washington, D.C., November 18, 1976.

TABLE 4

HUD NEF Interpretation

NEF Level	Residential Site Category
Less than NEF 30	Normally acceptable for any type of construction.
Between NEF 30 and NEF 40	Normally unacceptable for single-unit residential construction; acceptable for multi-unit construction with soundproofing.
Greater than NEF 40	Unacceptable for practically all types of residential construction area restricted to agricultural, outdoor recreational or industrial uses.

Source: Cawthorn, Jimmy M. and Brown, Christine G. "Effect of Advanced Aircraft Noise Reduction Technology on the 1980 Projected Noise Environment Around Patrick Henry Airport." NASA Technical Memorandum. Langley Research Center. Hampton, Virginia, 1974.

where

w_i = time of day weighting for sample i

$L_{A,i}$ = A-level for sample i

n = number of samples of L_A in a 24-hour period.

II.9 Noise Exposure

A set of computer programs has been generated for the U.S. Department of Transportation for the computation of noise exposure values due to aircraft operations around airports. The collection of programs is called the Integrated Noise Model (INM). The INM system is available from the Federal Aviation Administration (FAA), Washington, D. C., at a nominal charge. The INM will compute noise exposure values for the following noise metrics: Noise Exposure Forecast (NEF); Day-Night Sound Level (L_{dn}); Community Noise Equivalent Level (CNEL); Equivalent Sound Level (L_{eq}); Aircraft Sound Description System (ASDS); and an experimental metric called Daily Overall Sound Exposure (DOSE). The use and description of INM is presented in references [1] and [4]. The calculations of NEF and L_{dn} noise exposures can be represented by the following generalized equation:

$$NE = 10 \log \{ \sum_{i=1}^{n} (aD_i + bE_i + cN_i)\ 10^{(EL_i/10)} \} - A \qquad (6)$$

where,

NE	represents noise exposure (either NEF or L_{dn})
a, b, c	day, evening and night weighting factors (for NEF and L_{dn}, c = 16.7 and c = 10 respectively while a = b = 1 for both metrics)
D, E, N	actual number of day, evening and night (respectively) flight operations

EL single event exposure level (i.e., EPNL for NEF, or NEL for L_{dn})

A 88.0 for NEF or 49.4 for L_{dn}.

Equation (6) is a concise representation of the noise exposure calculation process. This calculation, briefly, consists of determining the relative position of an aircraft to a point of interest and the physical components computed (i.e., thrust and velocity). Then, the single event level is found and the weighted number of identical operations of the type being considered are factored into the computations. Finally, a cumulative sum of noise exposure comprising the contributions from all distinctly different kinds of operations from all the aircraft flights on all the ground tracks is computed yielding the final total exposure.

One last metric will be presented. This metric not only uses a multiple event noise metric but simultaneously weights the impact with population figures. This metric is then used in formulating an objective in the mathematical representation of the airport noise problem (section IV).

II.10 Noise Impact Index

The noise impact index (NII), may be used for comparing the relative impact of one noise environment with that of another. "It is defined as the sound level weighted population divided by the total population under consideration" [15]. The formula for this index is

$$NII = \frac{LWP}{P_{Total}} \tag{7}$$

where

LWP = sound level weighted population

P_{Total} = total population under consideration.

The sound level population represents the integrated effect of given noise environments on a particular population. LWP is represented mathematically by

$$LWP = \int P(L_{dn}) \cdot W(L_{dn}) d(L_{dn}) \qquad (8)$$

where

$P(L_{dn})$ = population distribution function

$W(L_{dn})$ = day-night average sound level weighting function

$d(L_{dn})$ = differential change in day-night average sound level.

An effective approximation for the calculation of the Noise Number Index is

$$NII = \frac{\sum_k P_k W(L_{dn})_k)}{\sum_k P_k} \qquad (9)$$

where

P_k = population in area k

$W((L_{dn})_k)$ = day-night average sound level weighting function

$(L_{dn})_k$ = day-night level for area k.

An example of $W(L_{dn})$ would be the sound level weighting function for overall impact analysis described in [15]. The analytic expression for this function is,

$$W(L_{dn}) = \frac{[3.364 \times 10^{-6}][10^{0.103L_{dn}}]}{[0.2][10^{0.03L_{dn}}] + [1.43 \times 10^{-4}][10^{0.08L_{dn}}]} \qquad (10)$$

III. POTENTIAL STRATEGIES FOR REDUCING AIRPORT NOISE POLLUTION

Just as with the building of airports and the establishing of federal airways, considerable thought needs to be given to the long term effects of noise on populations living in proximity to major airports. The effect of aircraft noise pollution is not confined just to residents in the immediate area of the airport, as many complaints about noise come from people living at some distance from the airport. These people usually reside near either the approach paths into an airport or the take-off paths out of an airport. Proposed strategies for reducing airport associated noise usually consist of methods that airport operators may use to decrease the size of the NEF 40 and NEF 30 contours surrounding their airports. Recently, there has been a substantial amount of work being done in the area of engine modification as a way of reducing aircraft noise.

Flight procedures tend to be effective in reducing noise pollution but are controversial due to the safety aspects. Changes in flight procedures can affect either take-off or landing with the take-off involving primarily jet noise and the approach involving primarily machinery noise [7]. "In spite of the fact that much higher engine thrust is required for take-offs than landings, landing noise is frequently more annoying to the ear because of dominant fan noise" [11]. Landing approaches also tend to be less steep than take-offs, so a greater land area is exposed to this low latitude noise for a longer period of time [5].

Presently most aircraft use a 3° approach angle (one segment), or glide slope as it is called, which results in the aircraft being in its final landing configuration (flaps down, landing gear down), stabilized in speed and power at a height of not less than 1000 feet above the ground.

A two segment approach calls for a 6° glide slope from 3500 feet to 1000 feet. At 1000 feet a transition is made from a 6° glide slope to a 3° glide slope, with the transition complete at 700 feet above the ground [8]. The two segment approach would involve additional avionics in the aircraft and additional navigational aids on the ground, but would not require modification of any aircraft. Studies have stated that for the noisier aircraft in the current fleets, the two segment approach will reduce the NEF 30 area by 26%, but for the newer quieter aircraft the two segment approach would have little effect on noise reduction [2]. The airlines and Air Traffic Control (ATC) have objected to the two segment approach as a safety hazard and have instead devised a low drag/low power approach. This solution still uses a 3° glide slope with interception at 3000 feet as before, but with an intermediate flap setting instead of full flaps. Landing gear is delayed until 700 feet [8].

The most accepted method of noise abatement on take-off is to take-off under full power and climb at the steepest possible angle to gain height before flying over populated areas. Once the height is achieved to conform to safety procedures the engines may be throttled back during a flyover of populated areas. If this idea of a steep climbout is coupled with holding a constant speed instead of acceleration during climbout, a reduction of as much as .6 dB(A) may be realized [10]. Another method that may be used in some areas during climbout is the execution of turns in a direction aways from populated areas. This also assists in decreasing noise exposure and annoyance. One technique that may be used in good weather, and is presently used at Washington's National Airport, is the concentration of take-offs to strictly defined corridors. These corridors correspond to the Potomac River. In this method fewer people are inconvenienced, but the level of annoyance

within these corridors is increased [5]. If such corridors can be established over unpopulated, or favorably zoned land, then they can have a significant effect by decreasing the annoyance due to airplane noise.

Several parameters that affect the airport noise environment directly are,

(1) runway usage and trajectory selection for arriving and departing aircraft,

(2) total number of daily operations,

(3) operations by aircraft type and time period limitations.

There is little that can be done about runway orientation once an airport is operational. Even if an airport is in the design stages, safety considerations will dictate that runway orientation be in consonance with the prevailing winds in the area. Prevailing winds will also affect the utilization of runways, dictating on many occasions which runways may be used. When wind is not a factor, however, the option of runway and trajectory assignment may be exercised.

Another option that may be exercised in attempting to reduce noise around airports is to limit the number of daily flights of certain types of aircraft. This is a logical step since the NEF contours that quantify annoyance are calculated based on the fleet mix as well as the number of flights into and out of an airport within a 24-hour period.

Airport authorities cannot dictate the types of aircraft that utilize their airports, but they are aware that various types of aircraft have different effects on the noise pollution around their airports. Initially, without limiting the number of noisy aircraft, the managers may limit the time of day that a noisy aircraft may land. If the NEF or L_{dn} equations are examined, one will find that nighttime aircraft noise events are weighted

much greater than daytime aircraft noise events. If the number of noisy aircraft that are allowed to land at night are reduced, then the overall noise impact may be reduced.

One form of time period limitations was introduced by National Airport in Washington, D. C. as a part of its 1978 Draft Environmental Impact Statement [14]. Between the hours of 7 a.m. and 9 p.m., a maximum of 40 schedules per hour (take-off and landing) were proposed. From 9 p.m. until 9:30 p.m., 20 schedules were proposed. After 9:30 p.m., the number and type of aircraft that may depart or land is severely limited. Merely examining the NEF or L_{dn} equations will indicate that this action may reduce the noise exposure as measured by the response indices.

It is these last three parameters with which this research is primarily concerned. Our proposed objective of minimizing annoyance from aircraft noise will be sought by selecting the optimal trajectory selection and the optimal assignment of aircraft, by time period, servicing the airport of interest. This optimization will be conducted subject to constraints on demand for service, allowable number of operations, aircraft availability and geographical area allowable noise levels. The mathematical formulation of the problem of interest follows.

IV. AIRPORT NOISE MINIMIZATION MODEL

Assumptions that are made in developing the model for any airport of interest are:

a. The model is developed primarily for application to commercial airline traffic.

b. Approaching aircraft follow one of a group of fixed inbound trajectories. Likewise departing aircraft follow one of a group of fixed outbound trajectories.

The proposed model will be formed to include the following control parameters:

a. The number of aircraft of each type assigned to each specific trajectory in any designated time period for take-off,

b. The number of aircraft of each type assigned to each specific trajectory in any designated time period for landing.

The following symbols will be used in the formulation of the mathematical model:

VARIABLES

$X_{ikj\ell}$ = number of departures of type i aircraft with stage length k utilizing trajectory j during period ℓ

$Y_{ij\ell}$ = number of arrivals of type i aircraft utilizing trajectory j during period ℓ

CONSTANTS

A = area designation

i = type of aircraft designation

j = ground track designation

k = stage length designation

ℓ = time period designation

P = total affected population

R = runway number

NA = number of areas

ND = number of runways for departure aircraft

NI = number of types of aircraft

NJ = number of different ground tracks

NK = number of stage lengths

NL = number of time periods

NR	= number of runways
NV	= number of runways for arriving aircraft
N_d	= limitation on number of operations that use ground track d
N_p	= limitation on number of operations in time period p
N_r	= limitation on number of operations for runway r
N_s	= limitation on number of operations with stage length s
N_t	= limitation on number of airport operations per day
P_A	= population in area A
R_j	= set of ground tracks associated with runway R
V_A	= community response index critical value for area A
$NX_{i\ell}$	= number of type i aircraft available for take-offs during time period ℓ
$NY_{i\ell}$	= number of type i aircraft available for landing during time period ℓ
N_{tsdp}	= number of type t aircraft with stage length s with ground track d that are required during time period p

NOISE PARAMETERS

EPNL	= effective perceived noise level
$EPNL_{ijA}$	= effective perceived noise level for arriving aircraft of type i corresponding to ground track j experienced in area A
$EPNL_{ikJA}$	= effective perceived noise level for departing aircraft of type i with stage length k corresponding to ground track j experienced in area A
L_A	= A-Weighted sound pressure level

L_{dn} = day-night level

L_{eq} = equivalent sound level

NEF = noise exposure forecast

RI_A = community response index for area A

$W(RI_A)$ = weighting factor as a function of community response index for area A

IV.1 Objective Function

The objective function will be developed using population information and weighting factors discussed in Section II. For each of the grid areas shown in Figure 1, there is an associated population P_A that is assumed to be evenly distributed throughout the grid. If the populations of all the grid areas are summed, then the resulting P will be the entire affected population around an airport. The fraction of the population affected in any grid area A is:

$$P_A/P \qquad (11)$$

As is discussed in Section II.9, the selected community response index for grid A, $(L_{dn})_A$, will be utilized in conjunction with an associated weighting factor for objective function formulation. The selected objective is to minimize the sound level weighted population divided by the total population under consideration. Mathematically, this is represented as:

$$\text{minimize } \left[\sum_{A=1}^{NA} W((L_{dn})_A)(P_A)/P \right] \qquad (12)$$

IV.2 Constraints

Airport authorities seeking to reduce noise and still service passenger demand for their airports may impose various related operating constraints.

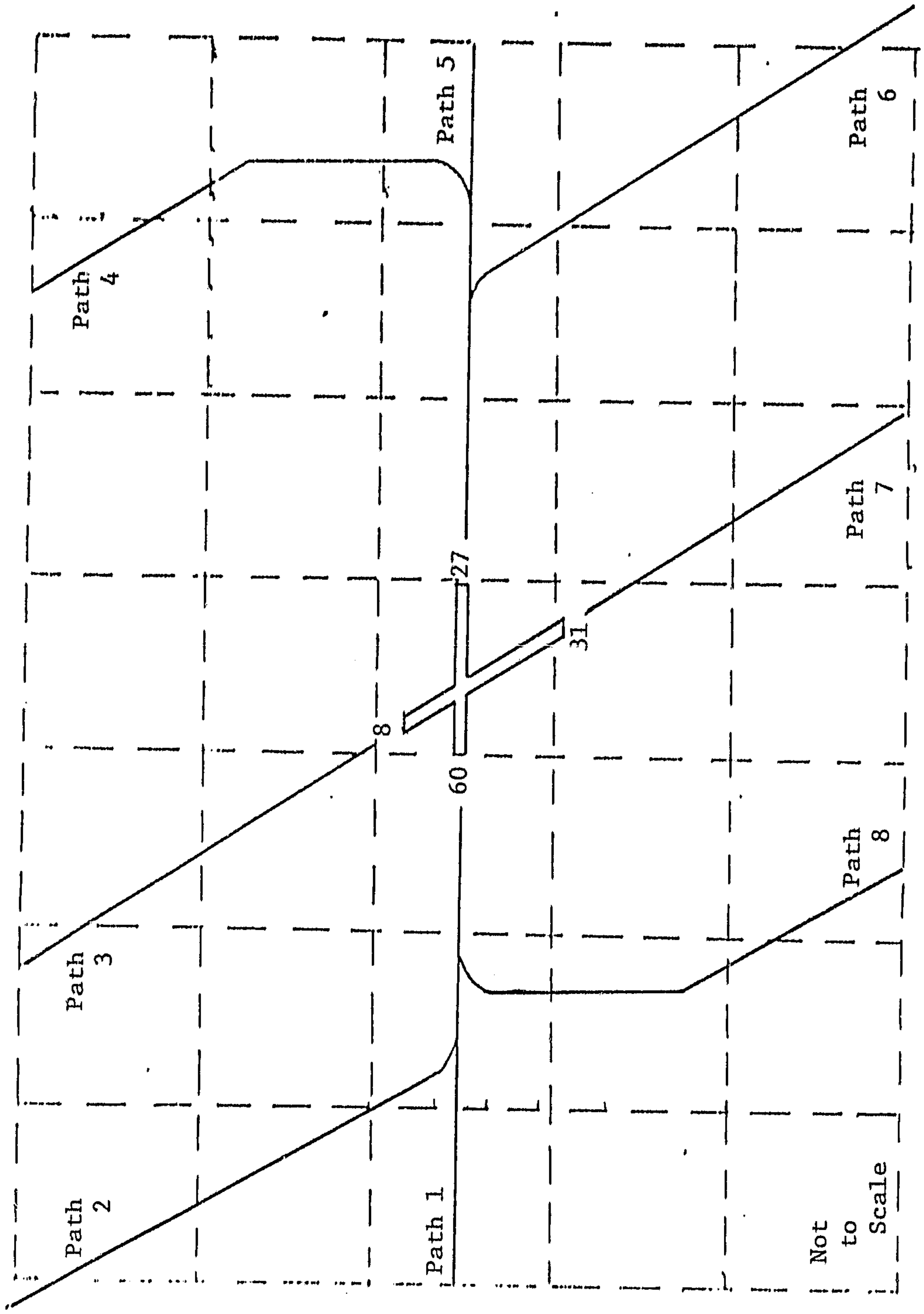

Figure 1 Airport with Grid Squares

IV.2.1 Flight Limitations

For any given airport flight limitations may be imposed for many different reasons and consist of many different constraints on aircraft operations. The flight limitations of primary interest in this research are those operational constraints that may be imposed in an attempt to improve the noise environment around an existing airport. The operational flight constraints formulated in this research are:

1. The annoyance as measured by a specified community response index may not exceed critical values for specified communities in the airport vicinity.
2. The number of certain types of aircraft that may operate into and out of a given airport cannot exceed some upper limit.
3. The number of certain types of operations such as the take-offs of long stage length aircraft may be limited.
4. Certain runways may only be used during certain periods or a limitation on the number of operations per period for any given runway may be specified.
5. Certain trajectories that correspond to specified ground tracks may only be used during certain periods or a limitation on the number of operations per period for any given ground track may be specified.
6. The total number of operations per time period may be constrained.

These flight limitations are now formulated mathematically:

1. The annoyance as measured by some community response index for a given area, A, must not exceed some critical value, V_A

$$RI_A \leq V_A \qquad A = 1, \ldots, NA \tag{13}$$

For example if L_{dn} was selected as the community response index then (13) would appear as a function of the decision variables as

$$10 \log_{10} \sum_{i=1}^{NI} \sum_{j=1}^{NJ} \sum_{k=1}^{NK} \{(X_{ijk1} + 10X_{ijk2})10^{(NEL_{ijkA}/10)}$$

$$+ (Y_{ij1} + 10Y_{ij2})10^{(NEL_{ijA}/10)}\} - 49.4 \leq V_A$$

$$A = 1, \ldots, NA \qquad (14)$$

2. The number of aircraft type t allowed to operate in and out of a given airport is limited to N_t operations per day

$$\sum_{k=1}^{NK} \sum_{j=1}^{NJ} \sum_{\ell=1}^{NL} X_{tkj\ell} + \sum_{j=1}^{NJ} \sum_{\ell=1}^{NL} Y_{tj\ell} \leq N_t \qquad t = 1, \ldots, NI \quad (15)$$

3. The number of take-offs with stage length s is limited to N_s operations per day

$$\sum_{i=1}^{NI} \sum_{j=1}^{NJ} \sum_{\ell=1}^{NL} X_{isj\ell} \leq N_s \qquad s = 1, \ldots, NK \qquad (16)$$

4. The number of operations for runway r is limited to N_r per day

$$\sum_{i=1}^{NI} \sum_{k=1}^{NK} \sum_{j\epsilon R_j} \sum_{\ell=1}^{NL} X_{ikj\ell} + \sum_{i=1}^{NI} \sum_{j\epsilon R_j} \sum_{\ell=1}^{NL} Y_{ij\ell} \leq N_r,$$

$$r = 1, \ldots, NR \qquad (17)$$

5. The number of operations corresponding to ground track d is limited to N_d per day

$$\sum_{i}\sum_{k}\sum_{\ell} X_{ikd\ell} + \sum_{i=1}^{NI}\sum_{\ell=1}^{NL} Y_{id\ell} \leq N_d \qquad d = 1, \ldots, NJ \tag{18}$$

6. The total number of operations in time period p must not exceed N_p

$$\sum_{i=1}^{NI}\sum_{k=1}^{NK}\sum_{j=1}^{NJ} X_{ikjp} + \sum_{i=1}^{NI}\sum_{j=1}^{NJ} Y_{ijp} \leq N_p \qquad p = 1, \ldots, NI \tag{19}$$

IV.2.2 Aircraft Availability

Only a limited number of the various types of aircraft servicing an airport will be available during each time period for either landing or departure. This may be expressed analytically as

$$\sum_{j=1}^{NJ} Y_{ij\ell} \leq NY_{i\ell} \qquad i = 1, \ldots, NI; \quad \ell = 1, \ldots, NL \tag{20}$$

$$\sum_{k=1}^{NK}\sum_{j=1}^{NJ} X_{ikj\ell} \leq NX_{i\ell} \qquad i = 1, \ldots, NI; \quad \ell = 1, \ldots, NL \tag{21}$$

IV.2.3 Passenger - Aircraft Demand

Passenger demand may be established for any given airport. Then passenger demand may be translated into aircraft demand. Such demands may take the form of requiring at least N_ℓ operations of interest along a subset of tracks ϕ_n (where n denotes the subset of interest) during time period ℓ. For departures this may be represented by,

$$\sum_{i=1}^{NI} \sum_{j \epsilon \phi_n} \sum_{k=1}^{NK} X_{ijk\ell} \geq N_\ell \qquad \ell = 1, \ldots, NL; \quad n = 1, \ldots, NN \qquad (22)$$

where, NN = the number of track subsets.

This is one of the simplest ways in which passenger demand may be accounted for. More eleborate demand relationships could be derived and utilized if desired.

Collectively Equations (12) through (22) define a mathematical model for this research. This model may be classified as a nonlinear integer mathematical programming model. Solution techniques for such a model are discussed in the succeeding section.

V. SOLUTION TECHNIQUES AND COMPUTATIONAL RESULTS

Examination of the mathematical model formulation in Section IV reveals that the objective function is nonlinear. The constraints, with the exception of (13), are linear. It may be classified as a nonconvex programming problem of from 30 to 200 constraints with 100 to 500 variables for small to medium-small airports. Only the smallest of such problems would even be attempted through the direct application of one of the existing nonlinear optimization algorithms. Even if the attempt were made there would be no guarantee that the global optimum would be identified. The applications of interest may give rise to mathematical models with as many as a few thousand variables and several hundred constraints. The only optimization solution techniques that appear to be feasible for application to such size problems would require linearization (approximation) of all nonlinear equations.

V.1 Selected Solution Algorithm

The solution technique selected by this author is to use successive linear approximation for the nonlinear objective function and to consider the decision variables as continous. This algorithm, summarized below, uses gradient information to form successive linear objective function approximations. The objective equation in the following Step 1 is a linear approximation to the sum of all the population weighted L_{dn} values as a function of the control variables.

Step 1

$$\text{minimize } Z^L = \sum_{A=1}^{NA} (P_A/P)S_A \tag{23}$$

subject to all linear constraints

$$S_A = \sum_{i=1}^{NI} \sum_{k=1}^{NK} \sum_{j=1}^{NJ} \{10^{\left(\frac{NEL_{ikjA}}{10} - 4.94\right)} (X_{ikj1} + 10X_{ikj2})$$

$$+ 10^{\left(\frac{NEL_{ijA}}{10} - 4.94\right)} (Y_{ij1} + 10Y_{ij2})\} \tag{24}$$

letting,

$$c_{ikjA} = 10^{\left(\frac{NEL_{ikjA}}{10} - 4.94\right)} \quad \text{and} \quad d_{ijA} = 10^{\left(\frac{NEL_{ijA}}{10} - 4.94\right)}$$

implies $\quad S_A = \sum_{i=1}^{NI} \sum_{k=1}^{NK} \sum_{j=1}^{NJ} \{c_{ikjA}(X_{ikj1} + 10X_{ikj2})$

$$+ d_{ijA}(Y_{ij1} + 10Y_{ij2})\} \tag{25}$$

From Equations (14) and (25) we see that

$$L_{dn_A} = 10 \log_{10} S_A \tag{26}$$

which means that the set of nonlinear constraints in (14) may be handled by introducing the additional set of variables S_A $(A = 1, \ldots, NA)$ and upper bounding them, i.e.,

$$S_A \leq 10^{(V_A/10)} \qquad A = 1, \ldots, NA \tag{27}$$

This will provide a feasible solution to the problem but in no sense guarantees an optimum. Instead of the function given in Equation (23), the nonlinear objective function should be derived from Equation (12) upon substituting Equation (10) and Equation (26).

$$\text{minimize} \quad Z^N = \sum_{A=1}^{NA} (P_A/P)\left[\frac{3.364 \times 10^{-6} S_A^{1.03}}{.02S_A^{0.3} + 1.43 \times 10^{-4} S_A^{0.8}}\right. \tag{28}$$

However the Step 1 objective function has provided very good solutions to the original problem for the few example problems solved.

The reason for such an objective function is that it is linear in the decision variables and subject to linear constraints, hence corresponds to a linear programming problem. With sophisticated computer implementation, linear programming solution techniques are capable of solving very large

problems. For example, problems involving several thousand linear constraint equations and tens of thousands of variables are within the realm of possibility for the very efficient linear programming solution algorithms implemented on modern computers. However it should also be pointed out that to produce solutions to such large problems requires extensive efforts in data preparation, manipulation of the linear programming computer code, and interpretation of computational results.

Step 2

Obtain a truncated Taylor series expansion about the solution point from Step 1, say $\underline{S}^*$

$$u(\underline{S}) = Z^N(\underline{S}^*) + \nabla Z^N(\underline{S}^*)\ (\underline{S} - \underline{S}^*) \tag{29}$$

Now minimize (29) subject to the original linear constraints. This corresponds to solving another linear programming problem. Denote the solution to this linear program (29) as $\underline{S}^1$. Since $u(\underline{S})$ is constructed from the gradient of Z^N at $\underline{S}^*$, an improved solution point can be secured only if $u(\underline{S}^1) < u(\underline{S}^*)$. This will not guarantee that $Z^N(\underline{S}^1) < Z^N(\underline{S}^*)$ unless $\underline{S}^1$ is in the immediate neighborhood of $\underline{S}^*$. However, given $u(\underline{S}^1) < u(\underline{S}^*)$ there must exist a point, say $\underline{S}^2$, on the line segment between $\underline{S}^*$ and $\underline{S}^1$ such that $Z^N(\underline{S}^2) < Z^N(\underline{S}^*)$. To determine $\underline{S}^2$ one solves

$$\underset{\alpha}{\text{minimize}}\ Z^N(\underline{S}^* + \alpha(\underline{S}^1 - \underline{S}^*))$$

$$Z^N(\underline{S}^2) = Z^N(\underline{S}^* + \gamma(\underline{S}^1 - S^*)) = \underset{0 \leq \alpha \leq 1}{\text{minimize}}\ Z^N(\underline{S}^* + \alpha(\underline{S}^1 - \underline{S}^*)) \tag{30}$$

Set $\underline{S}^*$ equal to $\underline{S}^2$ and repeat Step 2 as many times as required to obtain the stopping condition, $u(S^1) \geq u(S^*)$. At this point no further improvement is possible.

The linear programs generated at the successive iterations of this algorithm differ only in the coefficients of the objective function. Therefore, the sensitivity analysis options available on a computerized linear programming solution algorithm mav be exercised to efficiently carry out all calculations required for the second through the last iteration. The solution to (30) may be obtained by the use of any one-dimensional search technique. Reference [9] provides a description of several one-dimensional search algorithms that could be used.

The MPS III (Mathematical Programming System) was utilized to implement this solution procedure on an IBM 370 computer. DATAFORM, a data management subsystem available through the MPS III package, was used to generate data, interface the required FORTRAN programs and produce computational reports for all application airports considered. The next section of this paper describes the application of the implemented solution procedure to an example airport.

V.2 Application Airport for Solution Procedure

The following describes a medium sized airport to which the solution procedure, just described, has been applied. The analysis was limited to commercial airline traffic for the particular airport of interest. A series of tables and figures, presented in Appendix A, are used in constructing the appropriate mathematical model. The computational results obtained from application of the solution algorithm to this example airport are displayed in Tables 5 and 6. Noise minimal operating scenarios for several other airports have been computed using this same solution algorithm. However, because of length considerations they are not presented in this paper.

TABLE 5

COMPUTATIONAL RESULTS FOR APPLICATION AIRPORT (DEPARTURES)

NII 0.17723

Number of Operations	Aircraft				Stage Length	Track Number	Time Period	
	DC-9	727	DC-8	L-1011			Day	Night
46		X			1	5	X	
10		X			2	5	X	
8		X			3	5	X	
6		X			4	5	X	
15			X		2	5	X	
4		X			1	5		X
2		X			2	5		X
2		X			4	5		X
5			X		1	5		X
2			X		1	6	X	
2			X		2	6	X	
60	X				1	8	X	
9	X				2	8	X	
10	X				3	8	X	
11		X			2	8	X	
8		X			4	8	X	
12				X	2	8	X	
7	X				1	8		X
2	X				2	8		X
1		X			3	8		X
1		X			4	8		X
1				X	4	8		X
2			X		1	12	X	
2			X		2	12	X	
1			X		1	12		X
COMPUTATIONAL RESULTS FOR APPLICATION AIRPORT (ARRIVALS)								
73	X					13	X	
4		X				13	X	
13			X			13	X	
8	X					13		X
2			X			13		X
86		X				14	X	
12				X		14	X	
10		X				14		X
1				X		14		X
6	X					15	X	
1	X					15		X

TABLE 6

COMPUTATIONAL RESULTS - Example 2

NII 0.14457 Departures

Number of Operations	Aircraft DC-9	Aircraft 727	Stage Length	Track Number	Time Day	Time Night
5	X		1	1	X	
1	X		1	1		X
5		X	1	2	X	
1		X	1	2		X
5	X		1	3	X	
1	X		1	3		X
4	X		1	4	X	
1		X	1	4	X	
1		X	1	4		X

TABLE 6 (Cont'd)
COMPUTATIONAL RESULTS (ARRIVALS)

5	X			5	X	
1	X			5		X
5		X		6	X	
1		X		6		X
5	X			7	X	
1	X			7		X
4	X			8	X	
1		X		8	X	
1		X		8		X

TABLE 7

COMPUTATIONAL RESULTS - Example 3

NII 0.15479 Departures

Number of Operations	Aircraft DC-9	727	A-300	Stage Length	Track Number	Time Period Day	Night
23		X		1	1	X	
9		X		2	1	X	
2		X		1	1		X
1		X		2	1		X
20	X			1	2	X	
3		X		1	2	X	
9		X		2	2	X	
2		X		1	2		X
1		X		2	2		X
23	X			1	3	X	
9		X		2	3	X	
2		X		1	3		X
1		X		2	3		X
22		X		1	4	X	
9		X		2	4	X	
1			X	1	4	X	
1		X		1	4		X
1		X		2	4		X
1			X	1	4		X

TABLE 7 (Cont'd)
COMPUTATIONAL RESULTS (ARRIVALS)

16	X				5	X	
17		X			5	X	
4		X			5		X
33		X			6	X	
4		X			6		X
33		X			7	X	
4		X			7		X
32	X				8	X	
1			X		8	X	
2	X				8		X
1		X			8		X
1			X		8		X

TABLE 8

COMPUTATIONAL RESULTS - Example 4

NII 0.27505 Departures

Number of Operations	Aircraft				Stage Length	Track Number	Time Period	
	DC-9	727	A-300	DC-10			Day	Night
71	X				1	1	X	
44	X				2	1	X	
23		X			3	1	X	
2		X			1	1		X
1		X			2	1		X
1		X			3	1		X
71		X			1	2	X	
44		X			2	2	X	
23		X			3	2	X	
2		X			1	2		X
1		X			2	2		X
1		X			3	2		X
7	X				1	3	X	
64		X			1	3	X	
44		X			2	3	X	
23		X			3	3	X	
2		X			1	3		X
1		X			2	3		X
1		X			3	3		X
71		X			1	4	X	
24		X			2	4	X	
11		X			3	4	X	
20			X		2	4	X	
12				X	3	4	X	
2		X			1	4		X
1		X			3	4		X
1			X		2	4		X

TABLE 8 (Cont'd)

COMPUTATIONAL RESULTS - Arrivals

Number of Operations	Aircraft				Stage Length	Track Number	Time Period	
	DC-9	727	A-300	DC-10			Day	Night
139		X				5	X	
6		X				5		X
19	X					6	X	
120		X				6	X	
1	X					6		X
5		X				6		X
139		X				7	X	
6		X				7		X
107	X					8	X	
20			X			8	X	
12				X		8	X	
5	X					8		X
1			X			8		X

TABLE 9

COMPUTATIONAL RESULTS - Example 5

NII 0.27505 Departures

Number of Operations	Aircraft						Stage Length	Track Number	Time Period	
	DC-9	727	707	A-300	L1011	747			Day	Night
29		X					1	1	X	
20		X					2	1	X	
3			X				2	1	X	
29			X				3	1	X	
5			X				4	1	X	
1					X		5	1	X	
1					X		6	1	X	
6						X	3	1	X	
6			X				1	1		X
1			X				2	1		X
4			X				3	1		X
2			X				4	1		X
1					X		5	1		X
1					X		6	1		X
29	X						1	2	X	
20	X						3	2	X	
23		X					2	2	X	
15		X					3	2	X	
5		X					4	2	X	
1						X	5	2	X	
1						X	6	2	X	
6		X					1	2		X
1		X					2	2		X
4		X					3	2		X
2		X					4	2		X
1						X	5	2		X
1						X	6	2		X
29		X					1	3	X	
23		X					2	3	X	
35		X					3	3	X	
1					X		5	3	X	
1					X		6	3	X	
5						X	4	3	X	
3		X					1	3		X
1			X				2	3		X
3			X				3	3		X
2			X				4	3		X
1					X		5	3		X
1					X		6	3		X
1						X	1	3		X
1						X	3	3		X

TABLE 9 (Cont'd)

COMPUTATIONAL RESULTS - (Departures Cont'd)

Number of Operations	Aircraft DC-9	727	707	A-300	L1011	747	Stage Length	Track Number	Time Period Day	Night
29	X						1	4	X	
23	X						2	4	X	
35	X						3	4	X	
5		X					4	4	X	
1						X	5	4	X	
1						X	6	4	X	
6		X					1	4		X
1		X					2	4		X
4		X					3	4		X
2		X					4	4		X
1						X	5	4		X
1						X	6	4		X
10			X				1	5	X	
12				X			3	5	X	
19					X		1	5	X	
23					X		2	5	X	
23					X		3	5	X	
5					X		4	5	X	
1					X		5	5	X	
1					X		6	5	X	
4			X				1	5		X
1				X			3	5		X
2					X		1	5		X
1					X		2	5		X
3					X		3	5		X
2					X		4	5		X
1					X		6	5		X
29		X					1	6	X	
23		X					2	6	X	
35		X					3	6	X	
5		X					4	6	X	
1						X	5	6	X	
1						X	6	6	X	
6		X					1	6		X
1		X					2	6		X
4		X					3	6		X
2		X					4	6		X
1						X	6	6		X

TABLE 9 (Cont'd)

COMPUTATIONAL RESULTS - (Arrivals)

Number of Operations	Aircraft						Stage Length	Track Number	Time Period	
	DC-9	727	707	A-300	L1011	747			Day	Night
96	X							7	X	
15	X							7		X
2						X		7		X
96		X						8	X	
11		X						8		X
6			X					8		X
51	X							9	X	
28		X						9	X	
17						X		9	X	
13		X						9		X
4						X		9		X
96		X						10	X	
17		X						10		X
8	X							11	X	
12				X				11	X	
76					X			11	X	
1				X				11		X
13					X			11		X
3						X		11		X
49		X						12	X	
47			X					12	X	
17			X					12		X

TABLE 10

Annoyance Comparison for Application Airports

	Minimum Operating Conditions	Current Operating Conditions
Example 1		
Noise Impact Index (NII)	0.17723	0.25648
†Number of Persons Highly Annoyed in 24 Hour Period	36,578	52,937
Example 2		
Noise Impact Index (NII)	0.14457	0.16792
†Number of Persons Highly Annoyed	4775	5546
Example 3		
Noise Impact Index (NII)	0.15479	0.18520
†Number of Persons Highly Annoyed	39,352	47,082
Example 4		
Noise Impact Index (NII)	0.27505	0.31086
†Number of Persons Highly Annoyed	744,385	841,286
Example 5		
Noise Impact Index (NII)	0.28658	0.37177
†Number of Persons Highly Annoyed	126,250	163,779

†These quantities were calculated using the formula on page B-5 of reference [15].

TABLE 6

Annoyance Comparison for Application Problem

	Minimum Operating Conditions	Current Operating Conditions
Noise Impact Index (NII)	0.17723	0.25648
†Number of Persons Highly Annoyed in 24 Hour Period	36,578	52,937

†These quantities were calculated using the formula on page B-5 of reference [15].

One can note from Table 6 that an estimated 31 percent reduction in the number of people highly annoyed may be achieved by utilizing the noise minimial operating procedure. This reduction in impact is typical of all airports analyzed, i.e., reductions of approximately 20-40% are achievable at the airports analyzed to date.

VI. CONCLUSIONS

An optimization mathematical model whose objective is to minimize a measure of annoyance due to the arriving and departing aircraft for a given airport has been formulated. A corresponding solution algorithm, relying upon the solution of linear programming problems, was subsequently developed and computational results for one operational commercial airport was presented. The solution algorithm, even though it does not guarantee to find the global optimum, should produce very good solutions for any given airport.

Our experience has been a 10-40 percent reductions in noise impacts are possible. This includes several airports that had previously implemented a noise preferential runway assignment system. Such systems are designed by airport authorities to reduce noise exposure taking into consideration population distributions, existing geographical features that might provide natural corridors (e.g., a river), airport instrumentation, weather conditions, etc. An especially attractive feature of the suggested solution algorithm is that it is capable of solving very large problems. For example, it would be feasible to attempt the solution of problems involving several thousand variables and 500 plus linear constraints.

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APPENDIX A

Data for Application Airport

TABLE A.1

Types of Aircraft Considered

Aircraft Type	Number of Stage Lengths*
DC-9-32	3
B727-200	4
DC-8-55	4
L-1011	4

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000 -1500 nautical miles) and 4 (1500-2500)

TABLE A.2

Demand for Incoming Flights

Runway Tracks	Day	Night
(15)24*	6	1
(13)12 R	90	10
(14)30 L	98	11

* The number in parenthesis designates the track number defined in Figure A.1. The following number designates the associated runway.

TABLE A.3

Take-off Flight Demands

Runway	Tracks	Day Stage 1	2	3	4	Night Stage 1	2	3	4
(6)	6	2	2	0	0	1	0	0	0
(11,12)	24	2	2	0	0	1	0	0	0
(1,2,3,4,5)	12R	46	25	8	6	6	2	0	2
(7,8,9,10)	30L	60	32	10	8	7	2	1	2

TABLE A.4

Available Aircraft for Arrivals

Type	Day	Night
DC-9-32	79	9
727-200	90	10
DC-8-55	23	3
L-1011	12	1

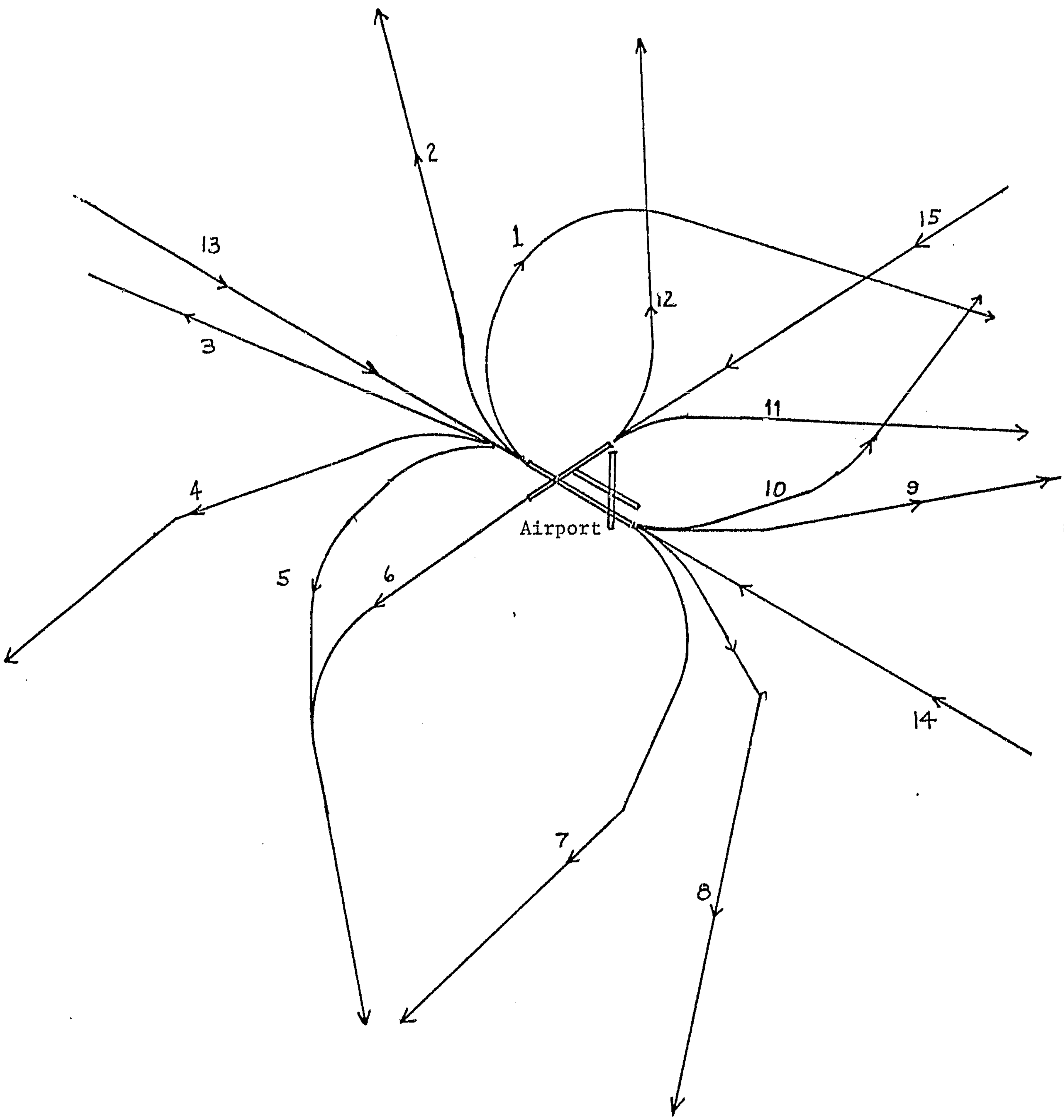
TABLE A.5

Available Aircraft for Departures

Type	Day	Night
DC-9-32	79	9
727-200	90	10
DC-8-55	23	3
L-1011	12	1

FIGURE A.1

Ground Tracks for Example Airport



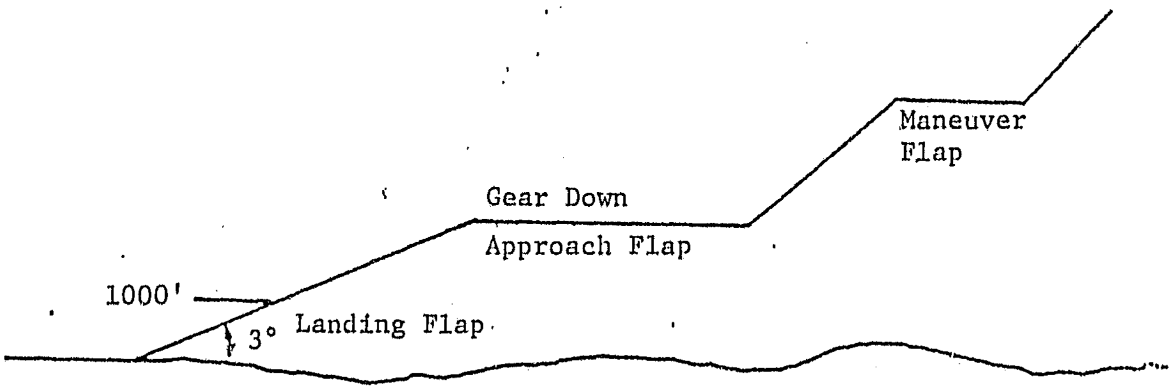


FIGURE A.2 3° Approach Profile. ("Airport Noise Reduction Forecast Volume II--NEF Computer Program Description and User's Manual." Study for Office of Noise Abatement, Department of Transportation by Wyle Research. Washington, D.C., October 1974.)

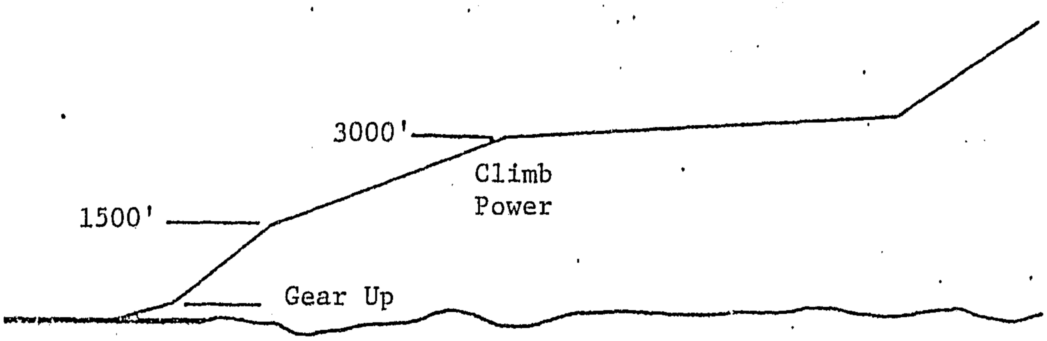


FIGURE A.3 Take-off Profile. ("Airport Noise Reduction Forecast Volume II--NEF Computer Program Description and User's Manual." Study for Office of Noise Abatement, Department of Transportation by Wyle Research. Washington, D.C., October 1974.)

FIGURE A.4

Population Areas in the Vicinity of Example Airport

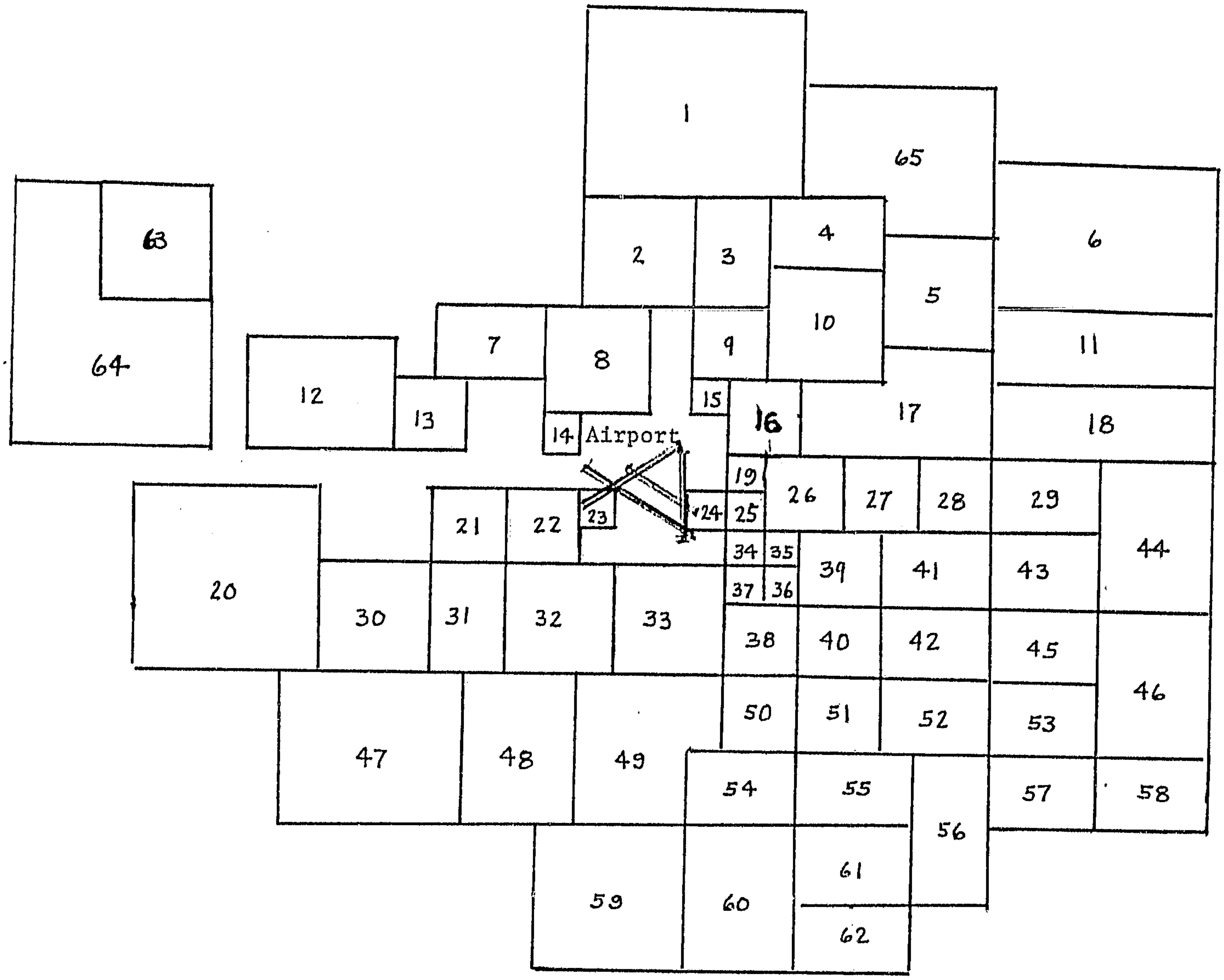


TABLE A.6

Population of Areas in Vicinity of Example Airport

Area	Pop	Area	Pop
1	20078	34	879
2	16176	35	2127
3	8022	36	1161
4	8732	37	2591
5	11887	38	7447
6	12317	39	4294
7	4987	40	3585
8	5822	41	4401
9	7053	42	8060
10	19680	43	6075
11	9494	44	13940
12	3579	45	9578
13	5596	46	10334
14	946	47	6659
15	96	48	17991
16	8918	49	17268
17	5339	50	6714
18	9475	51	3048
19	532	52	8144
20	8874	53	13093
21	3799	54	5193
22	3996	55	5359
23	453	56	21192
24	1250	57	13785
25	1570	58	5640
26	4109	59	16827
27	5833	60	17408
28	6908	61	7977
29	10716	62	15239
30	11813	63	10034
31	2399	64	36311
32	15610	65	10852
33	10661		

APPENDIX B

Data for Application Airport

Example 2

TABLE B.1

Types of Aircraft Considered

Aircraft Type	Number of Stage Lengths*
DC-9-32	1
B727-200	1

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000-1500 nautical miles) and 4 (1500-2500)

TABLE B.2

Demand for Incoming Flights

Runway Tracks	Day	Night
(5) 03*	5	1
(6) 21	5	1
(7) 15	5	1
(8) 33	5	1

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000-1500 nautical miles) and 4 (1500-2500)

TABLE B.3

Take-Off Flight Demands

Runway Tracks	Day Stage 1	Night Stage 1
(1) 03	5	1
(2) 21	5	1
(3) 15	5	1
(4) 33	5	1

TABLE B.4

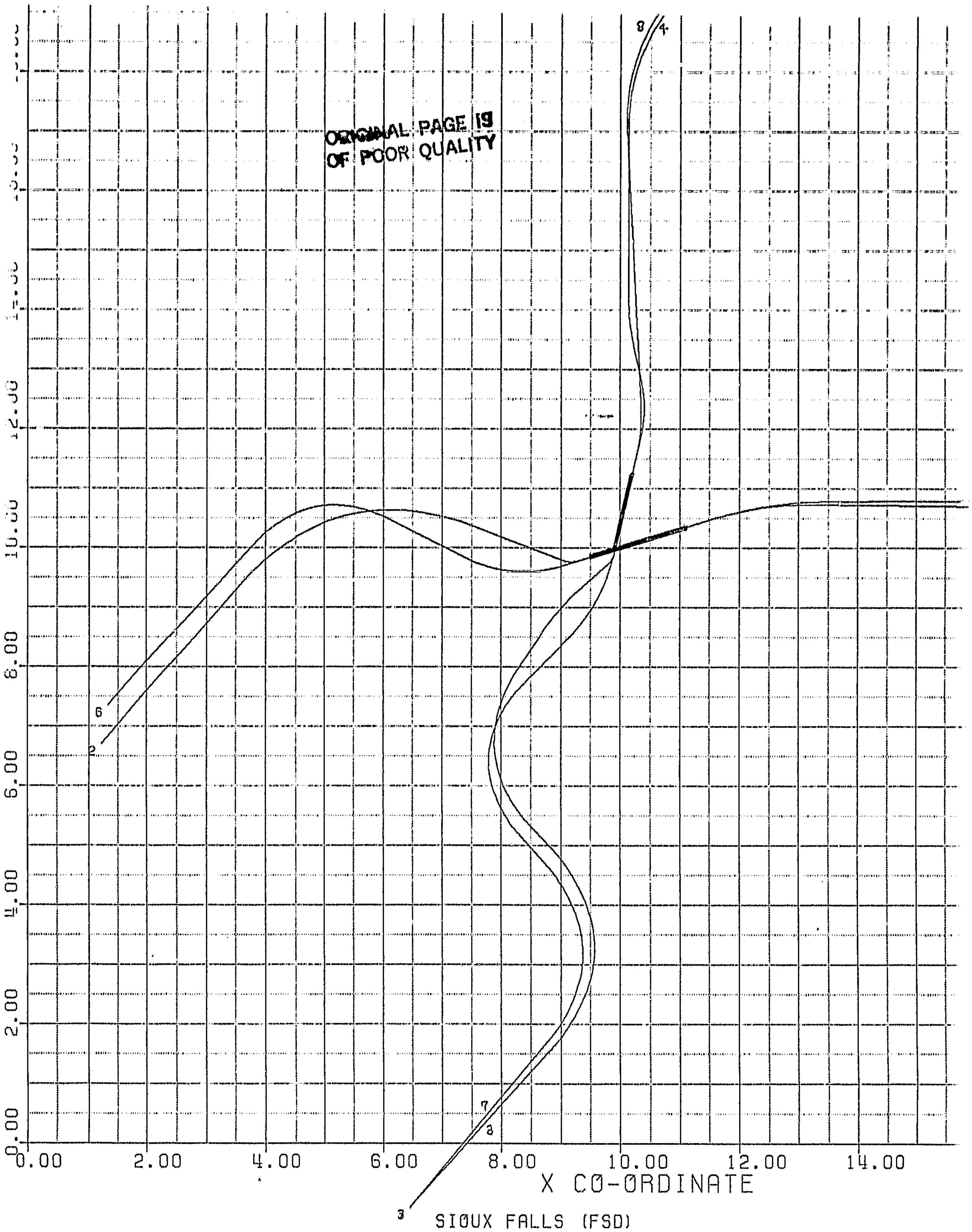
Available Aircraft for Arrivals

Type	Day	Night
DC-9-32	20	3
B727-200	6	2

TABLE B.5

Available Aircraft for Departures

Type	Day	Night
DC-9-32	20	3
B727-200	6	2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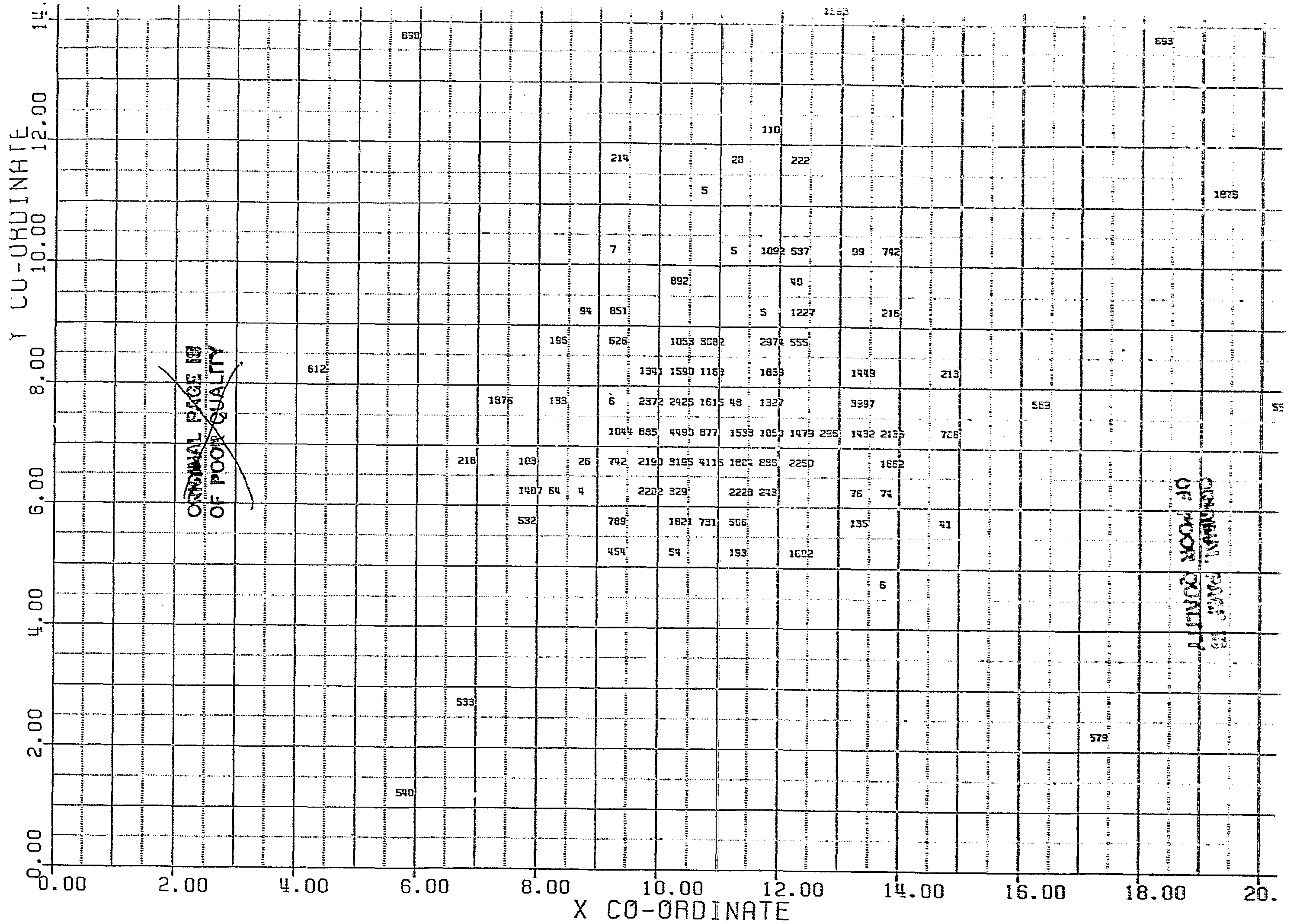
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APPENDIX C

Data Application Airport

Example 3

TABLE C.1

Types of Aircraft Considered

Aircraft Type	Number of Stages*
DC-9-32	2
B727-200	2
A-300	1

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000 -1500 nautical miles) and 4 (1500-2500)

TABLE C.2

Demand for Incoming Flights

Runway Tracks	Day	Night
(5) 12R*	33	4
(6) 30L	33	4
(7) 03R	33	4
(8) 21L	33	4

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000 -1500 nautical miles) and 4 (1500-2500)

TABLE C.3

Take-Off Flight Demands

Runway Tracks	Day		Night	
	Stage		Stage	
	1	2	1	2
(1) 12R	23	9	2	1
(2) 30L	23	9	2	1
(3) 03R	23	9	2	1
(4) 21L	23	9	2	1

TABLE C.4

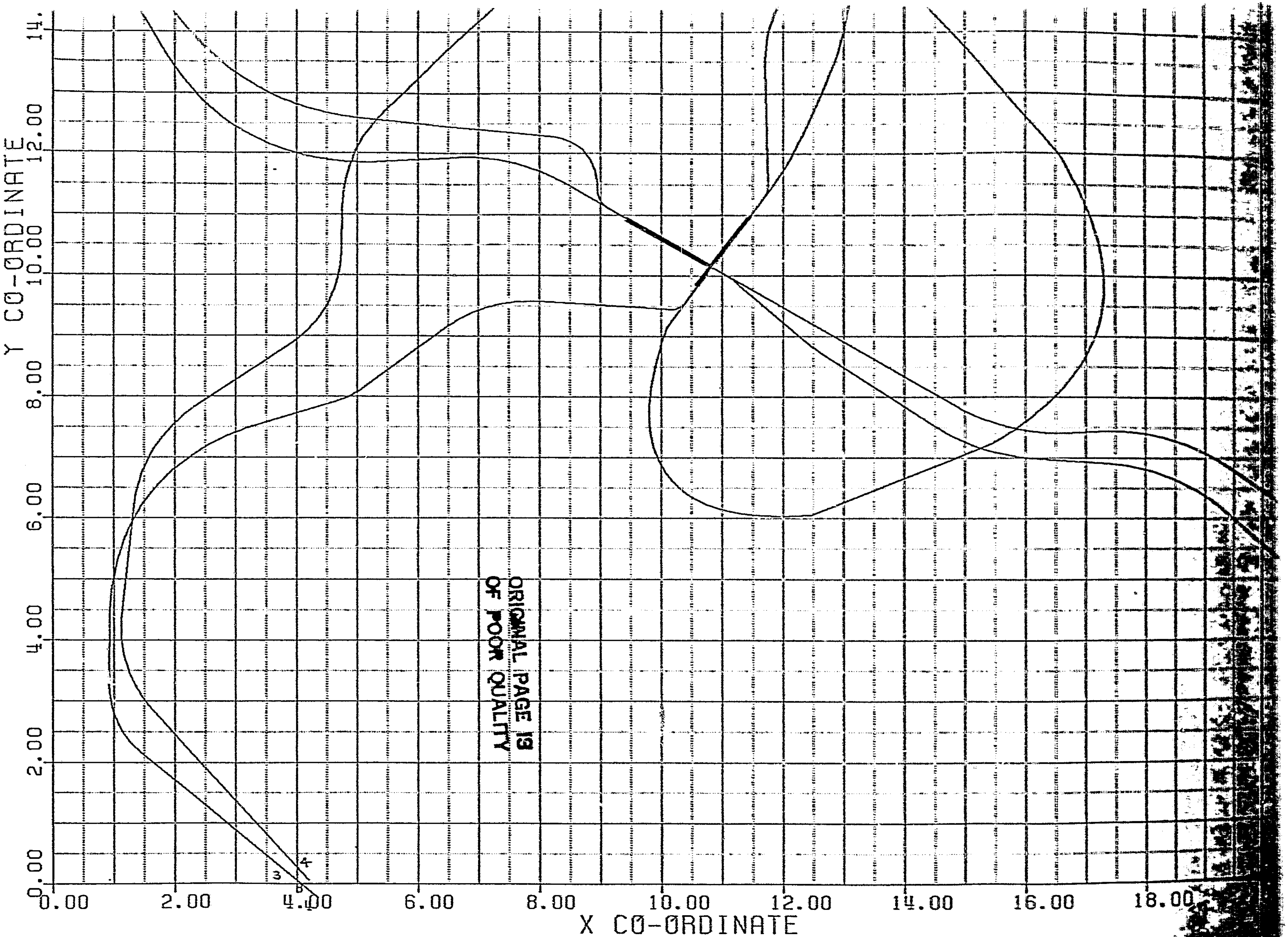
Available Aircraft for Arrivals

Type	Day	Night
DC-9-32	48	2
B727-100	84	15
A-300	1	1

TABLE C.5

Available Aircraft for Departures

Type	Day	Night
DC-9-32	48	2
B727-100	84	15
A-300	1	1



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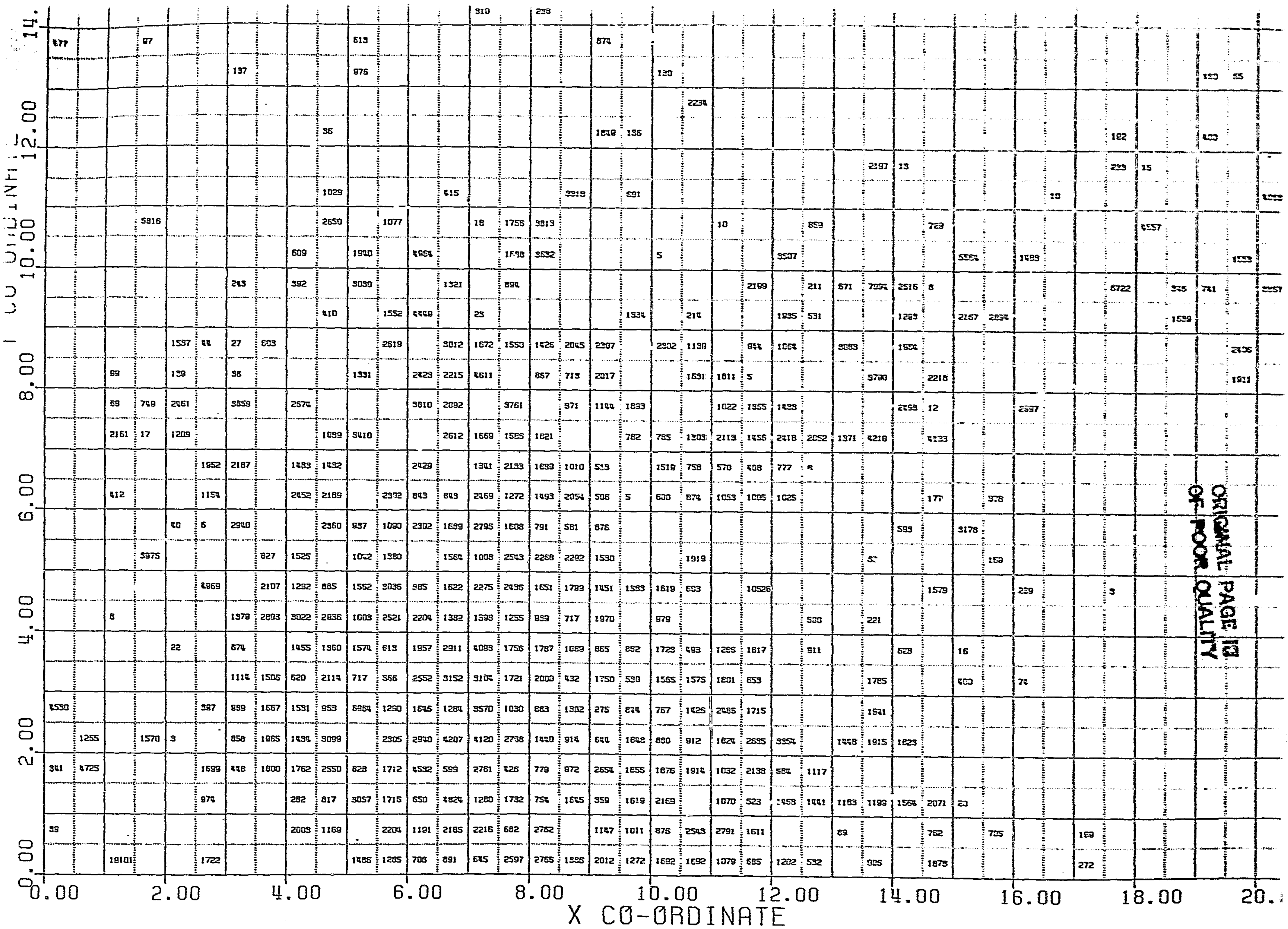

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APPENDIX D

Data for Application Airport

Example 4

TABLE D.1

Types of Aircraft Considered

Aircraft Type	Number of Stages*
DC-9-32	2
B727-100	3
A-300	2
DC-10-10	3

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000 -1500 nautical miles) and 4 (1500-2500)

TABLE D.2

Demand for Incoming Flights

Runway Tracks	Day	Night
(5) 04*	139	6
(6) 22	139	6
(7) 13	139	6
(8) 31	139	6

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000 -1500 nautical miles) and 4 (1500-2500)

TABLE D.3

Take-Off Flight Demands

Runway Tracks	Day			Night		
	Stage			Stage		
	1	2	3	1	2	3
(1) 04	71	44	23	2	1	1
(2) 22	71	44	23	2	1	1
(3) 13	71	44	23	2	1	1
(4) 31	71	44	23	2	1	1

TABLE D.4

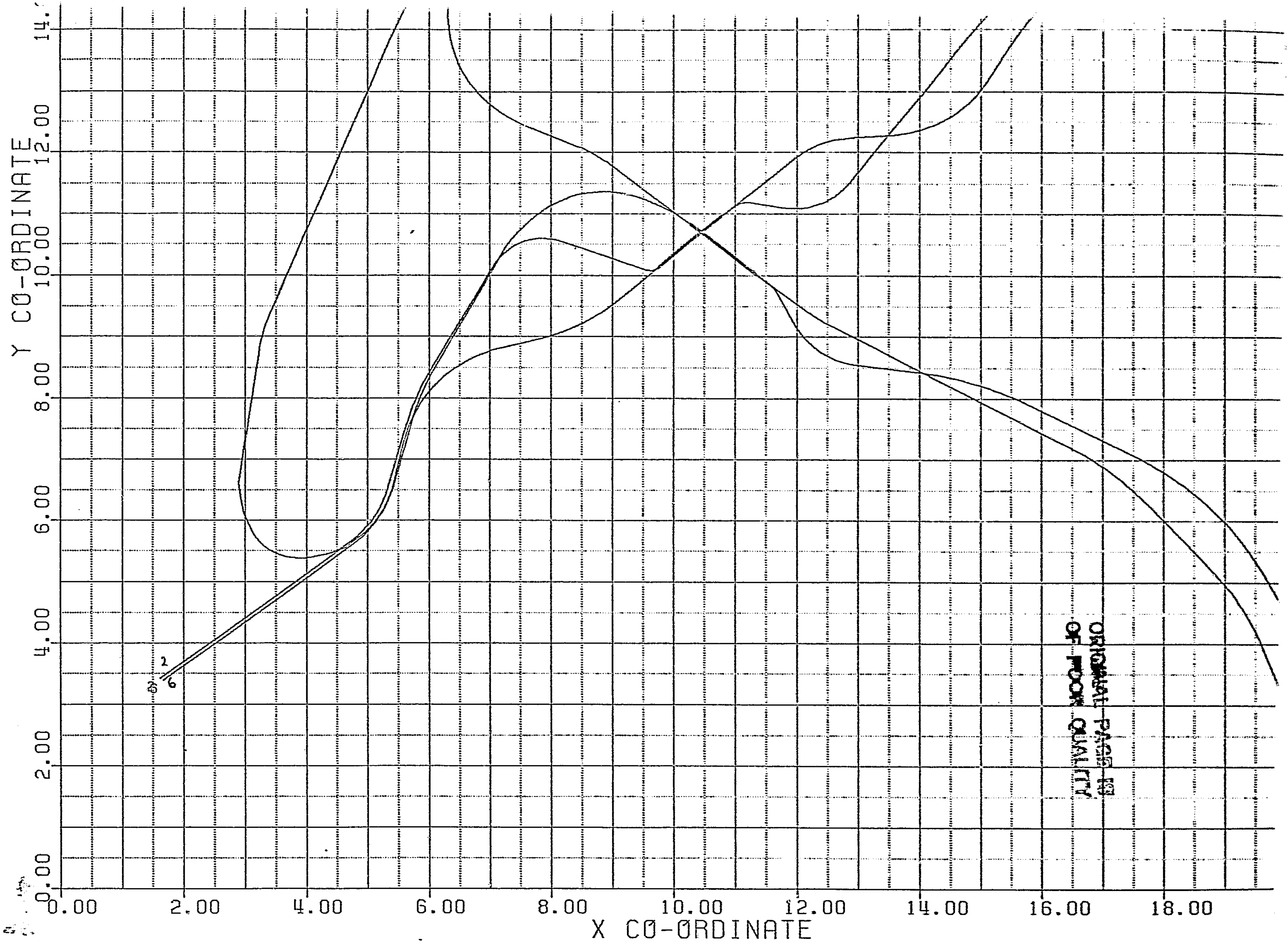
Available Aircraft for Arrivals

Type	Day	Night
DC-9-32	126	6
B727-100	398	20
A-300	20	1
DC-10-10	12	0

TABLE D.5

Available Aircraft for Departures

Type	Day	Night
DC-9-32	126	6
B727-100	398	20
A-300	20	1
DC-10-10	12	0



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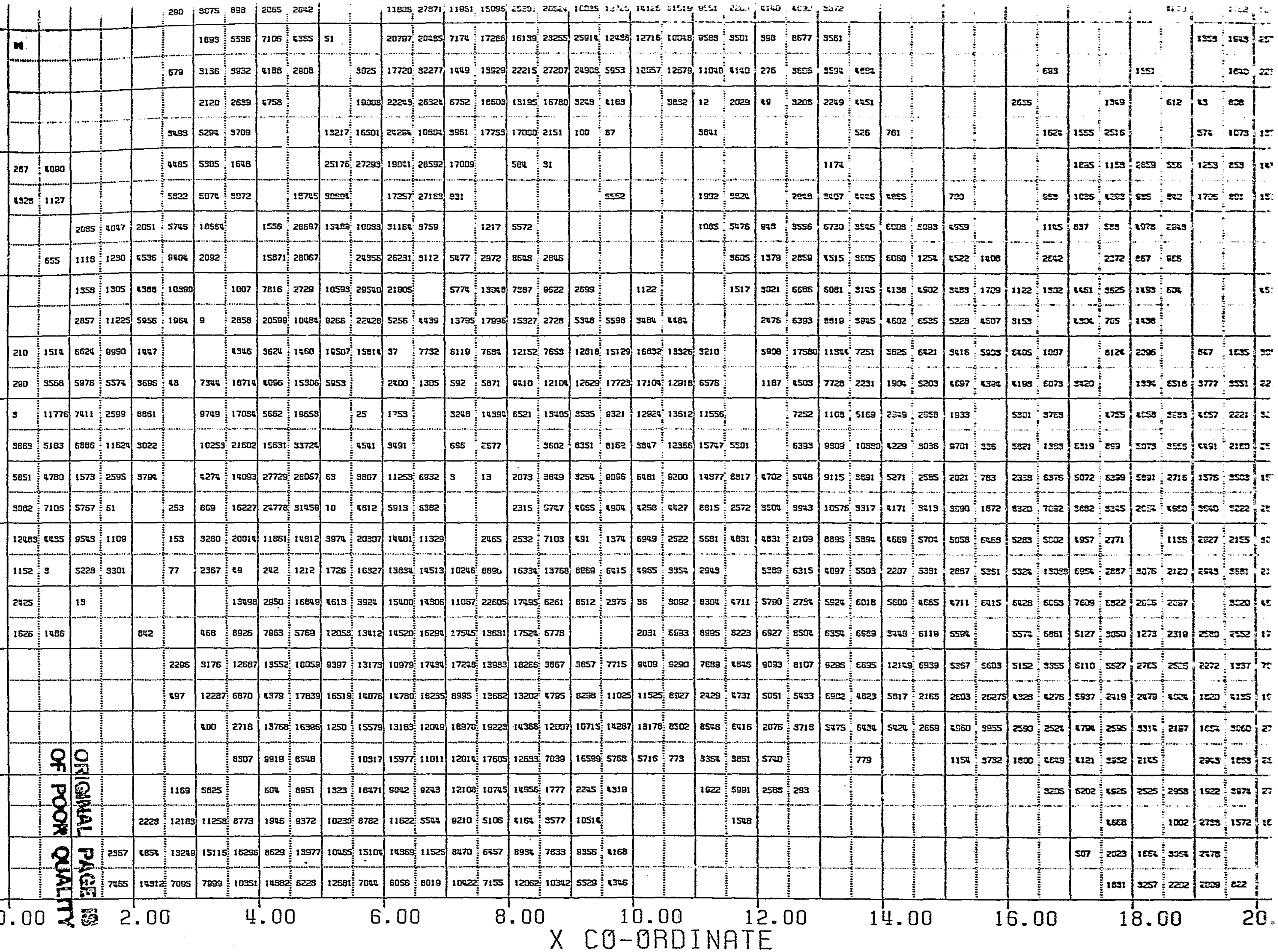
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APPENDIX E

Data for Application Airport

Example 5

TABLE E.1

Types of Aircraft Considered

Aircraft Type	Number of Stages*
DC-9-32	3
B727-100	4
B707-320	6
A-300	3
L-1011	6
DC-10-10	6

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000-1500 nautical miles) and 4 (1500-2500)

TABLE E.2

Demand for Incoming Flights

Runway Tracks	Day	Night
(7) 9R*	96	17
(8) 27L	96	17
(9) 9L	96	17
(10) 27R	96	17
(11) 12	96	17
(12) 30	96	17

* The stage length of a departing aircraft is a measure of the distance to the next destination. Stage lengths 1 (0-500 nautical miles), 2 (500-1000) nautical miles), 3 (1000-1500 nautical miles) and 4 (1500-2500)

TABLE E.3

Take-Off Flight Demands

Runway Tracks	Day						Night					
	Stage						Stage					
	1	2	3	4	5	6	1	2	3	4	5	6
(1) 9R	29	23	35	5	1	1	6	1	4	2	1	1
(2) 27L	29	23	35	5	1	1	6	1	4	2	1	1
(3) 9L	29	23	35	5	1	1	6	1	4	2	1	1
(4) 27R	29	23	35	5	1	1	6	1	4	2	1	1
(5) 12	29	23	35	5	1	1	6	1	4	2	0	1
(6) 30	29	23	35	5	1	1	6	1	4	2	0	1

TABLE E.4

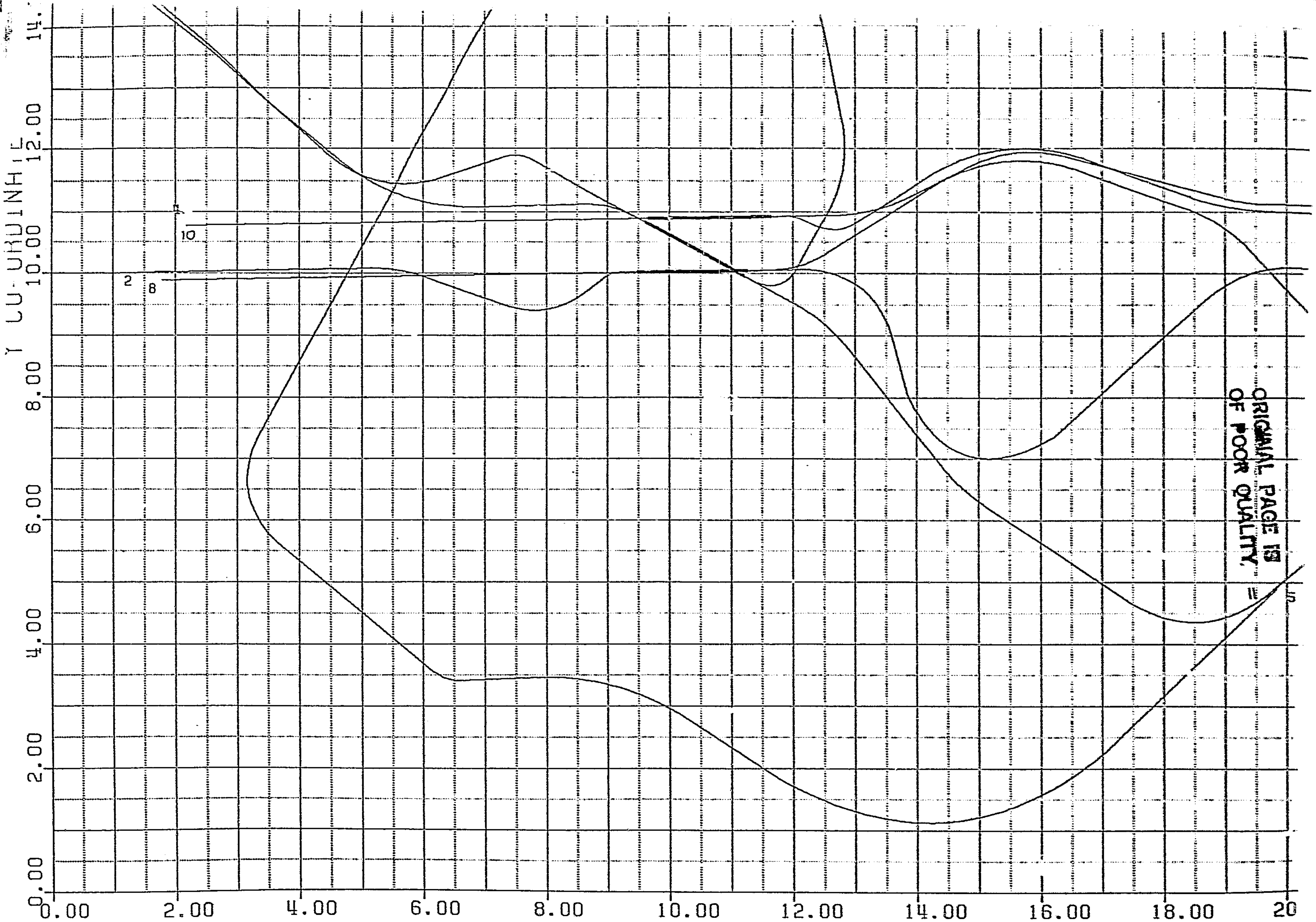
Available Aircraft for Arrivals

Type	Day	Night
DC-9-32	155	15
B727-100	271	42
707-320	47	23
A-300	12	1
L-1011	16	13
747-100	17	9

TABLE E.5

Available Aircraft for Departures

Type	Day	Night
DC-9-32	155	15
B727-100	276	42
707-320	47	23
A-300	12	1
L-1011	16	13
747-100	17	9



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